

EVIDENCE OF A NORTH-SOUTH ASYMMETRY IN THE HELIOSPHERE  
ASSOCIATED WITH A SOUTHWARD DISPLACEMENT OF THE  
HELIOSPHERIC CURRENT SHEET

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## ABSTRACT

Evidence of a north-south asymmetry in the global heliosphere, first inferred from Ulysses cosmic ray observations, is investigated using simultaneous Ulysses and WIND magnetic field observations. Such an asymmetry, presumably associated with a southward displacement of the Heliospheric Current Sheet (HCS), is expected to produce significantly different magnitudes of the radial field component,  $|B_R|$ , in the sun's north and south magnetic hemispheres or, alternatively, in the positive and negative magnetic sectors. Ulysses, while at high latitudes, spends time predominantly in first one and then the other hemisphere. As a consequence, measurements in the positive sector are obtained several months later than measurements made in the negative sector making comparisons susceptible to temporal changes. To address this ambiguity, the fields in both sectors observed by the WIND spacecraft in the ecliptic were compared. A large difference in  $|B_R|$  of 30 % was observed at WIND between Dec. 1994 and April 1995 with  $|B_R|$  larger in the south than in the north. Subsequent measurements show a gradual increase in the north (outward) radial component and a decrease in the south (inward) component ending in only a small difference by June, 1995. Thus, the WIND observations are consistent with a southward displacement of the HCS of  $\approx 10^\circ$  and with the energetic particle observations. The secular time variation, which occurred as the spacecraft transited from the south to the north hemisphere, explains why a significant north-south difference in  $|B_R|$  was not evident in the Ulysses measurements. The current sheet configuration and various questions and implications associated with these results are also discussed.

## 1. INTRODUCTION

Ulysses observations in the transit from the south to north solar poles have provoked interest in the possibility that the mid- or equatorial plane of symmetry of the energetic particles in the global heliosphere is offset toward the south by about  $10^\circ$ . Since the plane of symmetry of the particles is customarily identified with the Heliospheric Current sheet (HCS), which separates oppositely-directed magnetic fields from the sun's north and south poles, these observations suggest that there was a corresponding displacement or offset of the current sheet. Thus far, however, the published evidence based on Ulysses magnetic field observations has failed to reveal such a displacement. The present article continues the search for evidence in the magnetic field by comparing Ulysses observations with simultaneous measurements being made by the WIND spacecraft in the ecliptic plane. We discuss the inherent limitations associated with the Ulysses observations and provide evidence favoring the presence of a north-south asymmetry in the HCS location on the basis of the WIND data. We anticipate that these results will result in increased interest, not only in accounting for the cosmic ray results, but in possible offsetting of the HCS during other intervals and phases of the solar cycle.

Between September 1994 and May 1995, the Ulysses spacecraft executed a "fast latitude scan" passing from  $-80^\circ$  to  $+80^\circ$  heliographic latitude in only six months (Smith & Marsden 1995). Energetic particle measurements of both the galactic and anomalous cosmic rays revealed an asymmetry in the particle intensities with higher values in the north hemisphere (Simpson 1996; Simpson, Zhang & Bame 1996; Heber et al. 1996; McKibben et al. 1996). An apparent minimum in the intensities occurred at  $\sim -10^\circ$  heliographic

latitude and was consistent with this observation. The energetic particle investigators noted that some models of the Source Surface Neutral Line ((routinely supplied by Stanford Univ.), presumably representing the base of the HCS near the sun, were also consistent with a southward displacement of about 10°.

Ulysses magnetic field measurements were then examined for direct evidence of such an asymmetry. Seven crossings of the HCS observed at the spacecraft at various latitudes were used to obtain a profile of the current sheet which, qualitatively, did not appear consistent with a southward displacement (Smith & Balogh 1995). A quantitative comparison of the Ulysses data during the entire fast latitude scan based on integrating the magnetic flux from pole to pole was inconsistent with models which assumed an offset of 5° or 10° (Erdős & Balogh 1998). Since the radial component of the magnetic field has been found to be essentially independent of latitude, an asymmetry in the solid angles occupied by the two hemispheres would be expected to lead to a difference in the average values of  $r^2 |B_R|$  north and south, with the latter being larger because confined to the smaller of the two regions. However, any difference in the two values of the radial component adjusted for distance as measured at Ulysses was small and attributable to a concurrent time variation (Smith et al. 1997).

Thus, there has been an apparent inconsistency between the inferences drawn from the energetic- particle and magnetic- field data. Furthermore, the consequences of a north-south asymmetry for models of cosmic ray transport in the heliosphere are significant and, if such an asymmetry exists, it needs to be included in order to compare the models with the Ulysses observations.

## 2. EXPERIMENTAL ASPECTS

The following analysis is based on simultaneous magnetic field observations by Ulysses and WIND as well as IMP-8. Experimental details of these investigations are described in Balogh et al. (1992 ) and Lepping et al. (1995).

The basic parameter that is studied is the product of the radial component of the heliospheric magnetic field,  $B_R$  , and the square of the radial distance,  $r$ . This parameter can be regarded as a measure of solar magnetic flux along a streamline, an adjustment for the expected radial gradient consistent with flux conservation or an extrapolation of the radial component back to 1 AU. The values of  $r^2 |B_R|$  obtained at Ulysses during the pole-pole scan are shown in Figure 1 based on daily averages ( Smith et al. 1997). The polarities are negative in the southern hemisphere, positive in the north and alternate between the two sectors as the equatorial zone is crossed between  $\pm 20^\circ$ . The means and standard deviations for the intervals when Ulysses was located at latitudes above  $20^\circ$  ( outside the vertical dotted lines) are shown. The mean values south and north are equal to within about 6 % but with the field slightly larger in the south.

To reveal the possible influence of simultaneous time variations, in-ecliptic measurements at IMP 8 and WIND were compared with the Ulysses measurements. Figure 2 contains average values of  $|B_R|$  at the three spacecraft during the intervals when Ulysses was above  $\pm 20^\circ$ . Prior to December 1994, only IMP 8 measurements were available. After WIND was launched, we chose to plot the WIND data only. The simultaneous IMP 8 and WIND data agree on average ( to within about 0.1 nT) but the less complete coverage of the solar wind magnetic field, caused by periodic passages of IMP 8 through the Earth's magnetosphere, introduces larger variability into the measurements during a solar rotation. The in-ecliptic measurements also

tend to be more variable than those at Ulysses, a common feature of slow solar wind as compared to the fast, high latitude wind. Accordingly, all three sets of data have been smoothed by averaging over successive solar rotations.

In comparing Ulysses and in-ecliptic observations, we chose initially to restrict the latter to the same magnetic polarities or sectors that were being observed at Ulysses. Thus, the IMP 8 and WIND data were obtained in negative sectors when Ulysses was in the south and positive sectors when Ulysses was in the north hemisphere. The Figure shows good agreement between the various measurements. There is a slight tendency for the in-ecliptic values to be smaller in magnitude than the Ulysses averages. This difference is manifested by more IMP/WIND points lying above the Ulysses values on the left and below them on the right, i.e., closer to zero. ( This slight difference has been found in other Ulysses intervals but is not relevant to the present discussion and will be discussed elsewhere.) A slight decrease is also evident in the average values of  $|B_R|$  in the ecliptic which accounts for the slight decrease noted in the Ulysses measurements in Figure 1. The radial component and the field magnitude are known to decrease during sunspot minimum, so a decrease at this time is plausible.

Taken at face value, Figures 1 and 2 show no obvious evidence of a north- south difference in  $|B_R|$  such as would be expected for a southward displacement of the magnetic equator or HCS. However, there is a basic limitation to this analysis. The Ulysses trajectory generally restricts the observations to one polarity at a time and simultaneous data are not available in the opposite sector. In past studies of latitude differences in the HMF, contradictory evidence has been obtained regarding the extent to which the fields on the two sides of the HCS, or in the two sectors, are equal ( Luhmann et al. 1988; Burton et al. 1996). The obvious alternative is to examine  $B_R$  at the

in-ecliptic spacecraft which make observations in both sectors during a single solar rotation.

Figure 3 shows averages of the radial field components at WIND in positive and negative sectors, i.e.  $|B_R (+)|$  and  $|B_R (-)|$ , respectively, or, alternatively,  $|B_{RN}|$  and  $|B_{RS}|$ , while Ulysses was traveling from one hemisphere to the other. The vertical dotted lines and upper scale identify the location of Ulysses during this extended interval. At the start of the interval and the first 5 solar rotations, the fields in the two sectors are significantly different with  $|B_R (+)| < |B_R (-)|$ . (Although the IMP 8 data are not shown, this difference is also present in those data.) The north-south differences are quite large, 1 nT, are well outside the uncertainty in the measurements of 0.1 nT and are consistent with a southward displacement of the HCS.

Equally important is the evidence in figure 2 that this difference is no longer present by Y1995.3, i.e., by the time that Ulysses had reached 20° north latitude. The values of  $|B_R (-)|$  are more variable than  $|B_R (+)|$  but on average the two are approximately equal. Note that, after Y 1995.3, 4 values of the former are above, and 5 values are below, the latter.

As a check on the average measurements, the probability distributions of the WIND data in figure 3 in the two sectors were derived and are shown in Figure 4. The distributions are typical, including a difference between the average and most probable values (modes) associated with an asymmetry between small and large values (the distributions are not quite gaussian), for example, see the distributions in Smith & Balogh (1995). The means are 2.62 nT in the positive sector and -3.06 nT in the negative sector, a difference of about 15%. The standard deviations and number of points are also given in the figure so the standard errors can be computed. They are 0.003 and 0.004 nT

in the plus and minus sectors, respectively. Thus, the differences in the two means are statistically significant.

The most probable values of  $\approx 2.5$  and  $\approx 3.5$  nT, north and south, are significantly different and are consistent both qualitatively and quantitatively with the asymmetry in the averages. When the modes are plotted for each solar rotation, the variations track those in the averages quite closely and exhibit the same north-south differences. Thus, there is no reason to suspect any errors in the WIND measurements that might masquerade as the observed asymmetry.

These comparisons between the Ulysses and WIND measurements reveals that a time variation effectively obscured evidence of the north-south asymmetry in the Ulysses data. Figure 3 shows that the asymmetry tended to disappear toward the end of the Ulysses interval with  $|B_{RS}|$  decreasing in magnitude while  $|B_{RN}|$  simultaneously increased. The combination of Ulysses being restricted to a single sector and the presence of this time variation meant that Ulysses was unable to observe the asymmetry and that the Ulysses observations are consistent with its absence as concluded in previous studies.

### 3. DISCUSSION

WIND magnetic field data are consistent with a north-south asymmetry of the kind inferred from Ulysses cosmic ray observations and show that the Ulysses magnetic field measurements are not inconsistent with such as asymmetry as has been inferred previously. The WIND and Ulysses magnetic data are in agreement when allowance is made for a time variation obvious in the WIND data but not in the Ulysses data. The combined measurements provide a good example of why observations are necessary at

two different locations in order to avoid confusing time and spatial variations or, as in this instance, having time variations compensate for and mask spatial variations.

The combined data are also consistent with source surface calculations that show a north-south asymmetry during the Ulysses fast latitude scan which appears as a difference in the maximum latitudes of the source neutral line in the two hemispheres ( e.g., Heber et al. 1996, figure 1). In retrospect, such an asymmetry was also present during the two years prior to the Ulysses pole- to-pole crossing, implying that the asymmetry was present for a much longer period of time, but went unnoticed until the cosmic ray results implied an offset of some sort.

We note that photospheric magnetic field data from Kitt Peak Solar Observatory ( J. Harvey, private communication) and the Wilcox Solar Observatory reveal a difference in north-south polar field strengths consistent with the asymmetry in the Ulysses particle and field measurements. Figure 5 shows the WSO results. It is also noteworthy that this difference disappeared at about the same time as the differences in the WIND data in Figures 3 and 4. These supporting solar observations alleviate any concern that the disappearance of the asymmetry at WIND may seem to be too much of a coincidence to be believed. The solar results will be discussed in detail in a subsequent publication.

Bars labeled A and B in Figure 5 indicate time intervals during which the asymmetry and polar field strengths would propagate throughout the heliosphere at the solar wind speed and affect the cosmic ray fluxes. The asymmetry and magnetic field in the south were larger when Ulysses was in the south hemisphere (A) than the asymmetry and magnetic field in the north when Ulysses was in the north hemisphere (B). This change in field

strength can explain why the cosmic ray flux was larger in the north polar region than in the south polar region.

It might be supposed that the asymmetry is a feature of the slow solar wind , caused perhaps by slow-fast stream interactions, and thereby restricted to low latitudes. However, not only do the Ulysses data at high latitude agree with the WIND data at low latitude during the fast latitude scan, but during the interval when Ulysses was proceeding southward at large heliocentric distances, where interaction regions are more fully developed, the radial component agreed well with the corresponding measurements being made in the ecliptic by IMP 8. Thus, although such a possibility may be difficult to exclude completely, there is no obvious evidence in support of such a hypothesis.

The nature of such an " offset" is shown schematically in Figure 6. Since the solar wind and magnetic field ( disregarding the spiral) are basically radial without any significant north- south components, the current sheet must also be radial. Thus, the physical nature of the "offset" is actually a deflection of the HCS southward which makes it resemble a "Ballerina Skirt" more closely than ever. This figure clarifies the comments made earlier that the average radial fields above and below the current sheet will be different depending on the solid angles that they occupy in the two hemispheres. A configuration in which the current sheet is deflected southward, leading to the disappearance of the sector structure in the ecliptic near solar minimum, was reported many years ago (Wilcox,1972) but the consequences, especially for cosmic rays, was not appreciated nor did these "anomalous" observations attract much attention in other respects.

It is easily calculated that a deflection of 10° toward the south will lead to a ratio,  $B_{RN} / B_{RS}$ , which is consistent with the WIND measurements in the two sectors. The solid angles north and south for a given latitude angle,  $\delta$ , are:

$$\Omega_N = 2 (1 - \sin\delta) \text{ and } \Omega_S = 2 (1 + \sin\delta).$$

Hence, for an offset angle of  $\delta = -10^\circ$ ,

$$B_N / B_S = (1 + \sin(-10^\circ)) / (1 - \sin(10^\circ)) = 0.70.$$

Figure 3 shows that averages of  $2.5/3.5 = 0.71$  are in reasonable agreement with this ratio.

The existence of an "offset" in the solar magnetic field can be justified physically in a number of ways. One simple explanation is that the solar magnetic dipole is offset toward the south pole or, equivalently, a quadrupole having the proper sign is present in addition to the dipole. Such a situation would lead to a weaker polar cap field in the north than in the south, however, if the dipole field lines open into the solar wind, the magnetic flux issuing from the two poles would be the same (except for sign). Superficially, this condition would lead to weaker magnetic pressure over the north pole and a displacement of the neutral line and current sheet northward rather than southward. However, near the sun, other considerations enter because of possible accompanying asymmetries in the areas of the two polar coronal holes, the speeds of the solar wind from the poles which influences the ram pressures, etc. In fact, one of the scientific benefits in recognizing that north-south asymmetries can be present is the consideration of consequences for the sun and the global heliosphere which may result in improved theoretical models of the different regions.

The consequences of a displacement or deflection of the HCS and of a basic north-south asymmetry in the global heliosphere need to be assessed.

Theoretical efforts are now under way to incorporate an asymmetry into cosmic ray models. Such revisions will be simpler if the asymmetry is of long duration, for example, longer than the time it takes the solar wind to reach the outer boundaries of the heliosphere, so that steady state solutions are relevant. Such considerations also make it imperative that the presence or absence of an asymmetry be investigated in magnetic field observations and source surface calculations for intervals pre-dating the Ulysses epoch.

Preliminary simulations, based on the University of Arizona two-dimensional steady-state modulation model, show that the difference of  $|B|$  between the north and south as observed by Ulysses produces a north-south asymmetry in galactic cosmic rays of the same magnitude and nature as that observed by the cosmic ray experiments. The physical cause of the effect is that an increase (decrease) of the magnetic field magnitude decreases (increases) the cosmic ray transport coefficients, including both the drift velocity and the diffusion coefficients. Hence, the hemisphere with the increased magnetic field (south) has a reduced cosmic ray intensity because of the reduced particle transport. A paper reporting these results in more detail is in preparation.

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#### FIGURE CAPTIONS

Figure 1. Magnetic flux parameter vs. latitude during the Ulysses fast latitude scan.

Daily averages of  $r^2 B_R$  are shown as a function of time with latitude along the top scale. The means and standard deviations between  $\pm 80^\circ$  and  $\pm 20^\circ$  (outside the dotted vertical lines) are indicated. The mean field at these latitudes is somewhat larger in the south than in the north but possible time variations need to be considered before deciding whether or not the difference is consistent with an asymmetry between the two hemispheres.

Figure 2. The radial field component at Ulysses, IMP-8 and WIND.

Averages over successive solar rotations of  $r^2 B_R$  at Ulysses (solid lines) and  $B_R$  at in-ecliptic spacecraft (dashed lines) are shown over a more extended time interval than in figure 1 but including the fast latitude scan. The latter averages are for the same magnetic polarities as those being observed by Ulysses which was consistently above the heliospheric current sheet (negative at south and positive at north latitudes). The general agreement is impressive although the in-ecliptic fields appear to be slightly smaller than the field at higher latitudes.

Figure 3. Radial field component at WIND in the two magnetic sectors.

The modulus of  $B_R$  in the inward and outward directed sectors at WIND is shown during the year after the spacecraft first began obtaining solar wind data. The heliographic latitude of Ulysses at the same time is shown along the upper scale. During the first 5 solar rotations, the averages are significantly larger in the south/inward sector than in the north/outward sector consistent with a north-south asymmetry. The last 9 rotations show a

decrease in  $B_R$  (south) and an increase in  $B_R$  (north) such that the two parameters are nearly equal on average throughout the remainder of the year. Figure 4. Histograms of  $B_R$  at WIND in the two sectors.

The means, standard deviations and number of data points are shown for both histograms. The distributions are somewhat asymmetric but are typical of those commonly obtained in the ecliptic. The means and most probable values (modes) are both consistent with larger values in the inward/south sector.

Figure 5. Field Strengths at the Sun's North and South Poles during the Ulysses/WIND epoch.

The polar field strengths were measured by the Wilcox Solar Observatory and published at <http://quake.stanford.edu/~wso/Polar.ascii>. The line of sight field was measured between  $55^\circ$  and the poles and averaged each 10 days then smoothed to eliminate projection effects. The shaded region has been added to identify the time of the Ulysses fast latitude scan. A significant difference exists from 1994 to mid-1995 and mimics the difference in the radial fields north and south at WIND including the gradual disappearance of the difference by the end of the fast latitude scan. Bars labeled A and B indicate time intervals during which the asymmetry and polar field strengths would propagate throughout the heliosphere at the solar wind speed and affect the cosmic ray fluxes. The magnetic field in the south was larger when Ulysses was in the south hemisphere (A) than the magnetic field in the north when Ulysses was in the north hemisphere (B). This difference can account for the difference in the cosmic ray fluxes in the two hemispheres.

Figure 6. Schematic of an asymmetric current sheet.

This two dimensional diagram represents conditions near the sun where the effect of rotation can be neglected. Radial solar wind flow, which is established a few radii outside the solar corona, assures that the radial field and current sheet separating oppositely-directed fields are also radial. The current sheet takes the shape of a cone or skirt rather than a plane. It divides space into two unequal volumes, unequal areas on a sphere enclosing the sun, or unequal solid angles measured at the sun's center. Since the positive and negative magnetic fluxes must balance, average  $B_R$  ( south) exceeds  $B_R$  ( north) as indicated. The solar rotation axis can be considered to be inclined relative to the current sheet normal as usual so that the HCS wobbles up and down with both sectors being typically observed at low latitudes.

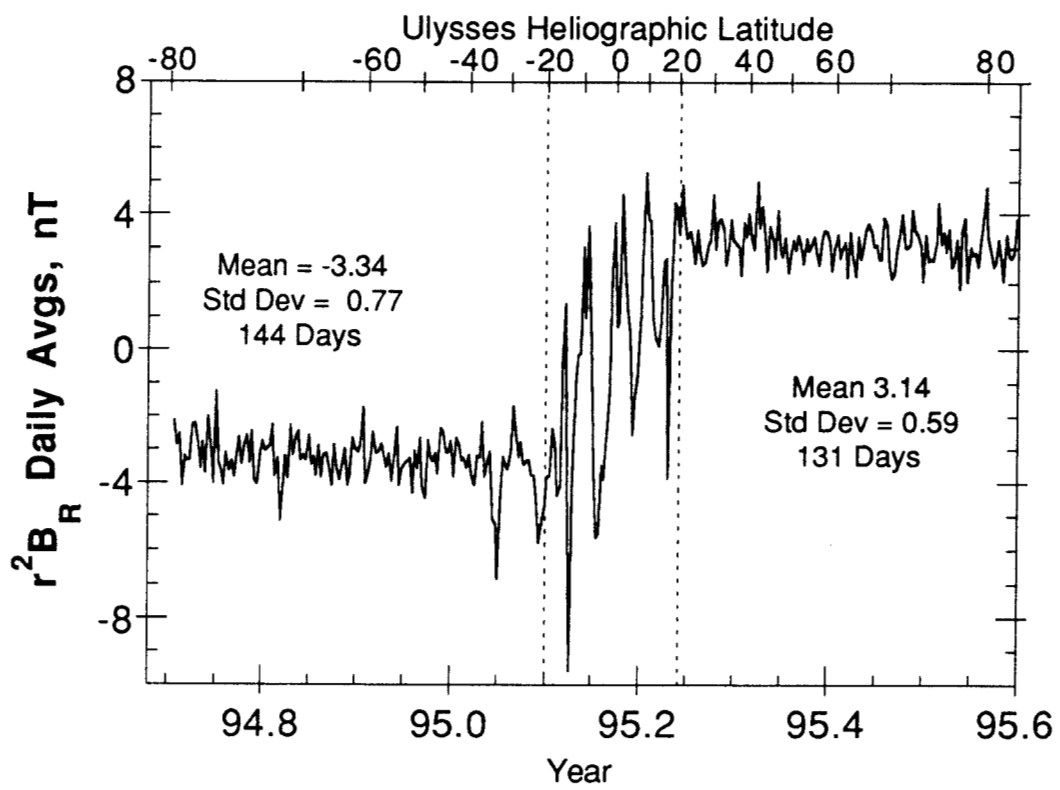


Figure 1

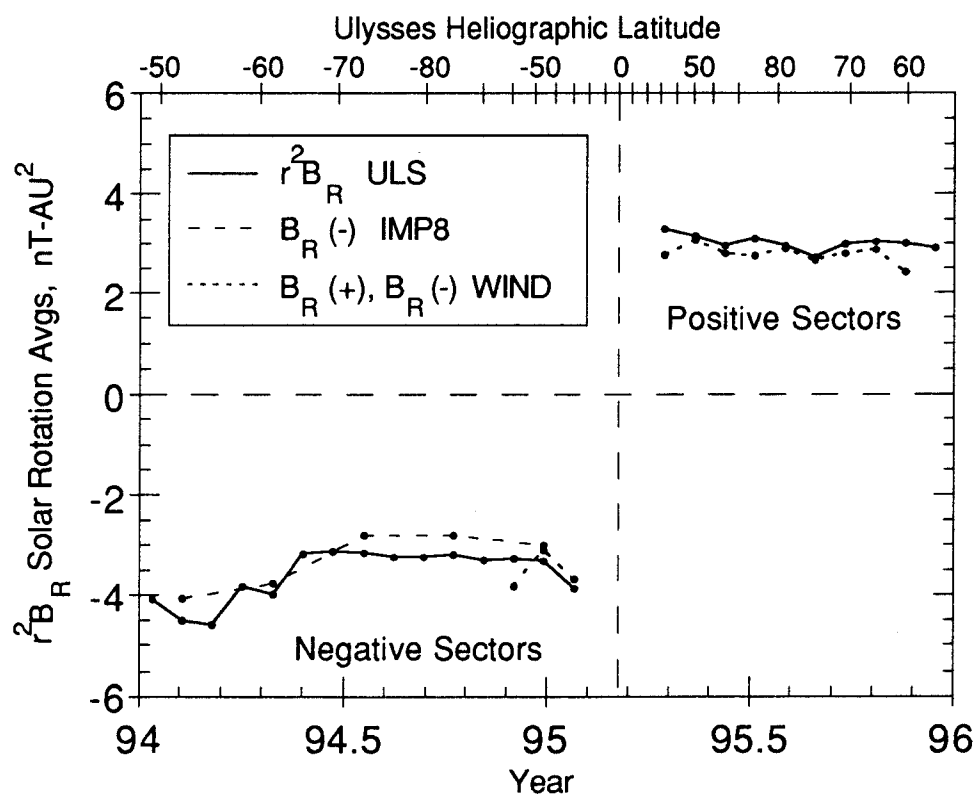


Figure 2

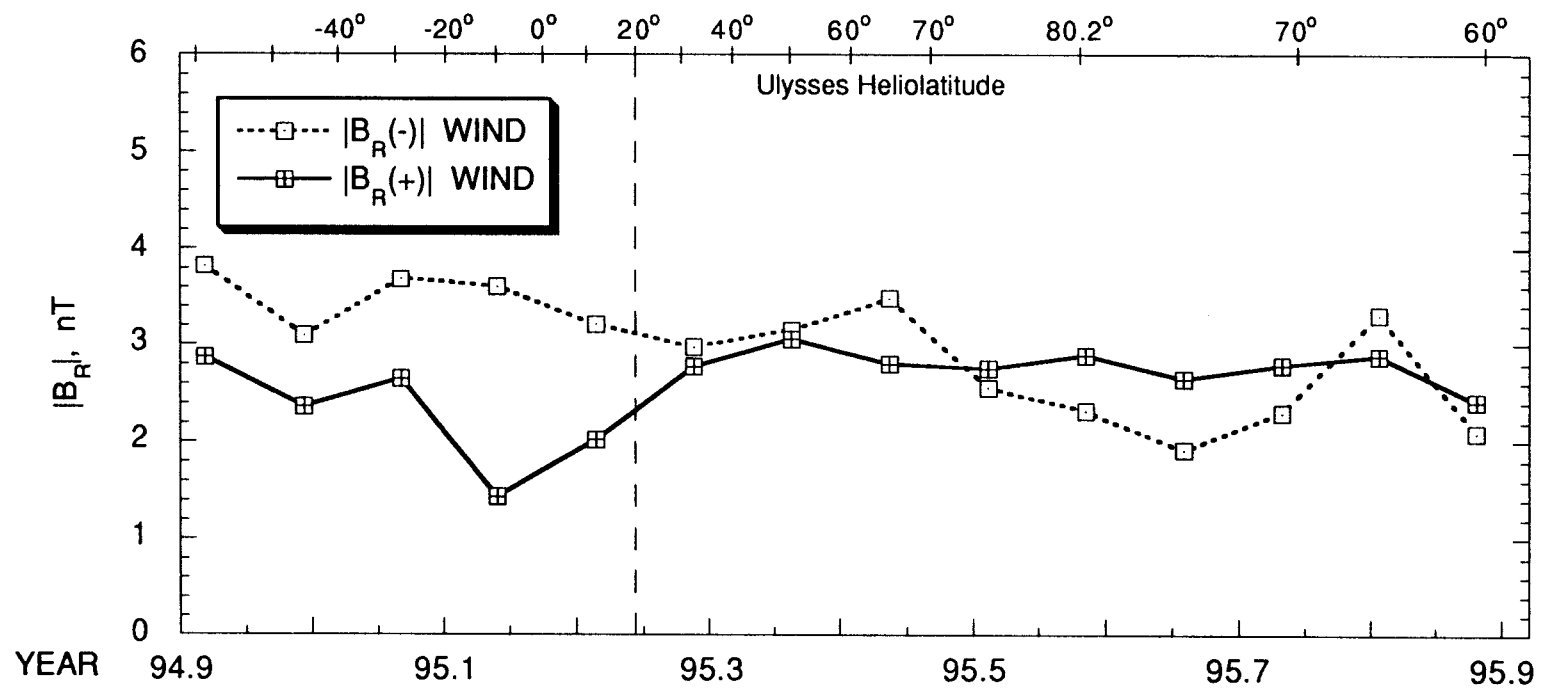


Figure 3

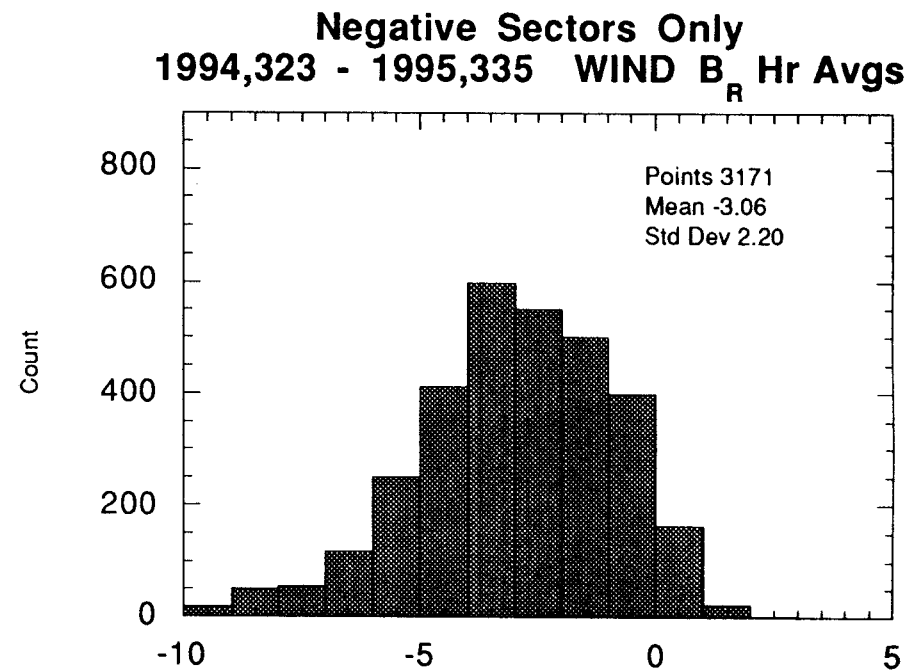
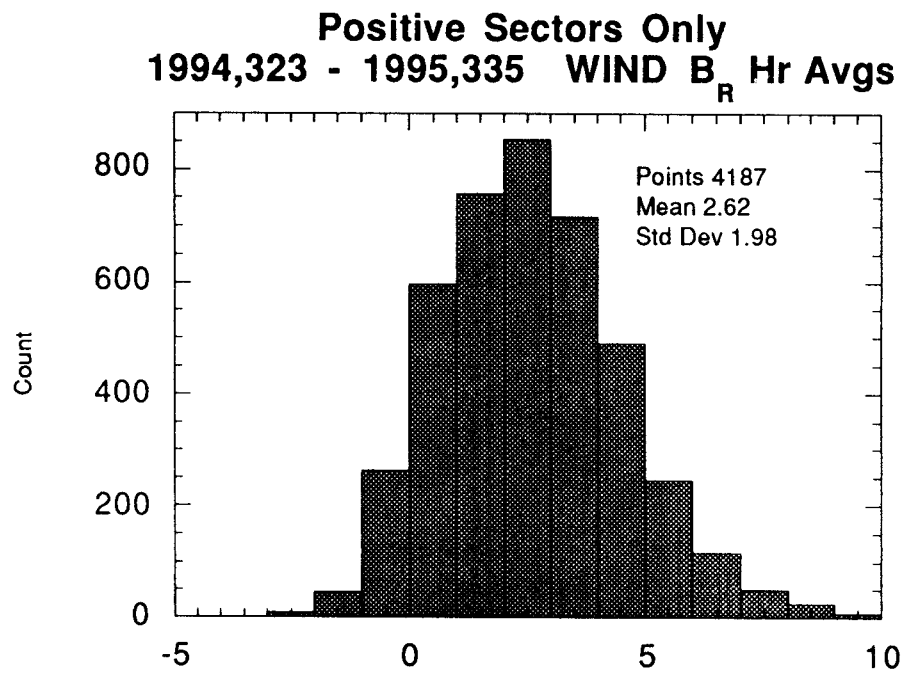


Figure 4

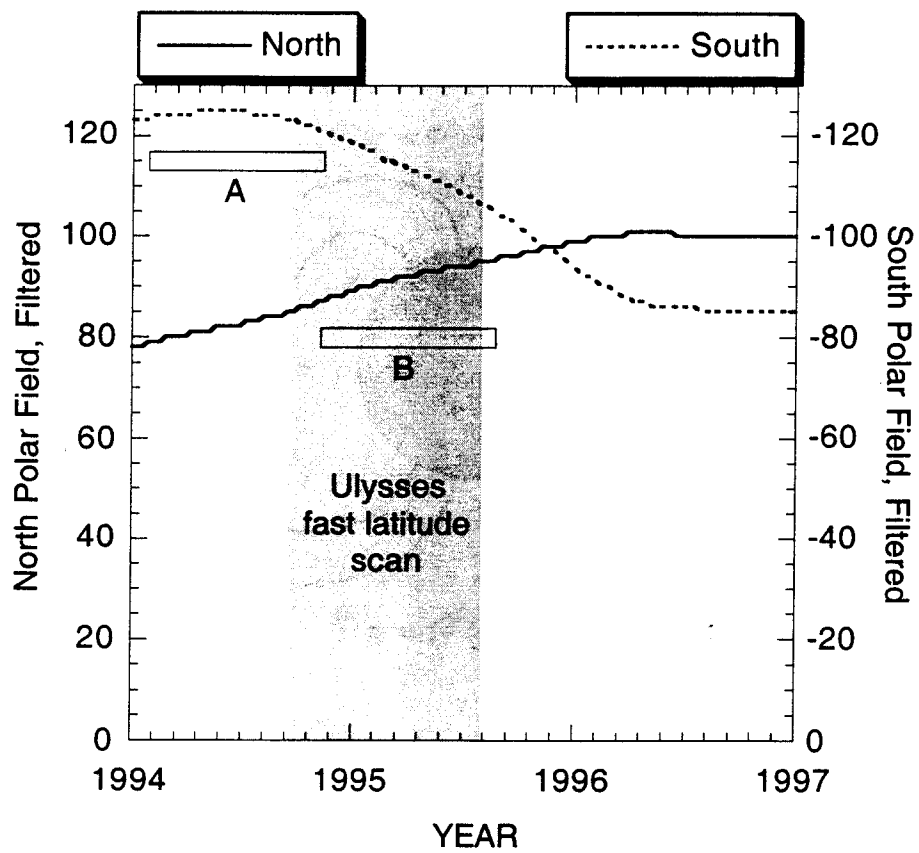


Figure 5